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METAL HYDRIDE PREHEATER FOR THE M2 DIESEL BURNER

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Preface

This report describes the results of a Phase I SBIR project to demonstrate the feasibility of preheating the catalytic generator of the M2 diesel burner using a metal hydride preheater. The work was conducted by Advanced Mechanical Technology, Inc. (AMTI) under DoD Contract No. DAAK60-97-C-9203 for the U.S. Army Soldier Systems Command, Natick, MA. The hydride preheater and source bed were designed and fabricated by Ergenics, Inc., Ringwood, NJ. Donald Pickard was the Technical Project Officer; Joseph Gerstmann was the Principal Investigator for AMTI, and Mark Golben was the Principal Investigator for Ergenics.

METAL HYDRIDE PREHEATER FOR M2 BURNER

1.0 INTRODUCTION AND SUMMARY

The military uses the M2 gasoline burner for a variety of food preparation needs in the field. With the conversion from gasoline to diesel/JP8 fuels by the military, logistical considerations dictate the conversion from a gasoline-fired cookstove burner to one that can burn diesel or JP8. The necessity of preheating the vapor generator with an air-atomizing preheat torch results in a smoky flame that requires the burner to be carried outdoors for ignition. A metal-hydride preheater can be employed to preheat the generator of a diesel-fired M2 burner up to its vaporization/gasification temperature, so that the burner can be supplied with a gaseous mixture that can be ignited cleanly indoors. This would eliminate the inconvenience and hazard of carrying a lit burner to its point of use, and would minimize the hand-pumping of air that is needed to power a preheater torch.

The technical approach to demonstrating the feasibility of preheating the catalytic generator of the M2 diesel burner using a metal-hydride preheater was to:

- 1) Identify the energy and preheat/regeneration temperature requirements of the generator and preheater;
- 2) Identify the interfacing requirements of the preheater, generator, and burner;
- 3) Design, fabricate and test a proof-of-concept metal-hydride preheater interfaced with a diesel burner;
- 4) Based on the test results, evaluate the overall feasibility of the approach.

Preliminary testing of an electrically heated generator showed that the originally proposed concept of preheating the catalytic generator of the burner would have resulted in excessive weight for the hydride system. An alternate approach of preheating only the "superheater", and using it to vaporize the fuel at start-up, was implemented instead. This resulted in an extremely compact and lightweight burner system that ignited cleanly and rapidly.

The Phase I results indicate that the "hydride superheater" is an effective means of obtaining clean ignition of a diesel cookstove burner. Furthermore, the resulting burner is considerably smaller and lighter than the M2 burner. Additional work is required to optimize the designs of the preheater and superheater, to scale-up the capacity of the burner, and to develop practical burner controls.

2.0 PHASE I RESULTS

2.1 Original Design

The modified M2 diesel burner consists of an M2 gasoline burner with a specially modified generator. The generator contains a catalyst which gasifies a portion of the diesel fuel, reducing re-condensation of the fuel and resulting in cleaner burner operation. The original design approach was to bond a metal hydride preheater coil to the outside of the cylindrical catalytic generator, as illustrated in Figure 1. The preheater coil is connected to a source bed containing a lower-temperature hydride. A manual-opening/automatic-closing hydrogen valve and a bypass check valve connect the preheat coil to the source bed.

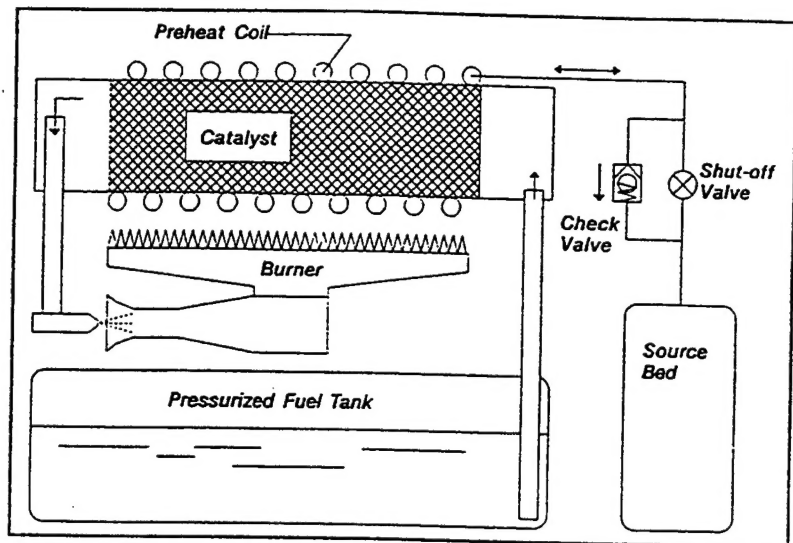


Figure 1. Metal Hydride Preheater

This concept requires the preheater to provide sufficient energy to heat the catalytic generator to the point that it can vaporize the fuel for start-up. The amount of energy required depends upon the fuel inventory of the generator, its temperature level and distribution, and the length of time that elapses before the burner can sustain the vaporization in the generator. The empirical approach to determining this energy requirement, and thus the size of the hydride preheater, was to heat the catalytic generator electrically, and to measure the electrical input necessary to achieve reliable ignition.

The electrically heated test generator is shown in Figure 2. The generator specifications are

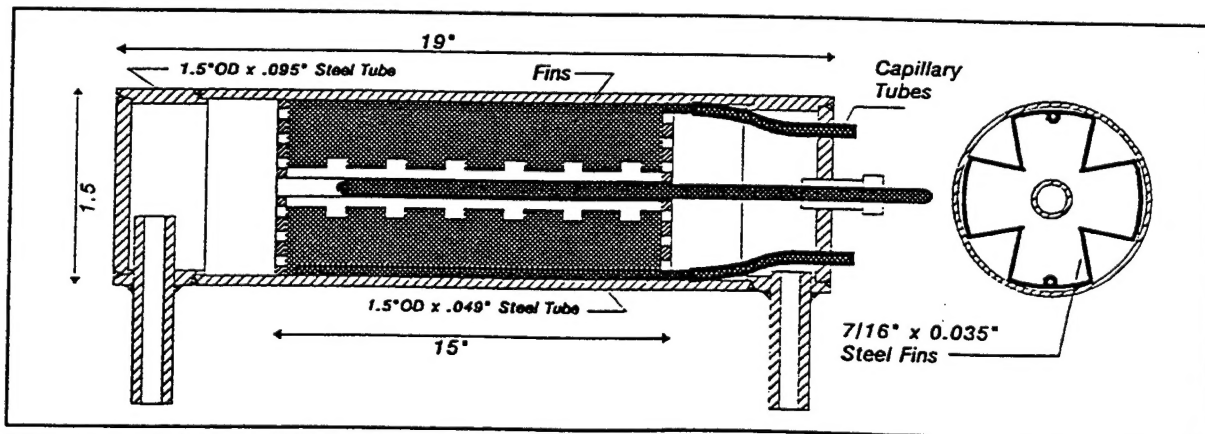


Figure 2. Electrically heated catalytic generator

listed in Table 1. The welded steel generator is heated by eight 1.5" ID x 2" long band heaters capable of up to 2,400 watts. Four thermocouples are installed to measure surface and internal temperatures. A central 1/8" OD stainless steel tube and two 1/16" OD tubes brazed to the inside wall of the shell are used to obtain temperature traverses of the core and wall, respectively. A fourth 1/16" OD sheathed thermocouple is used to obtain a radial temperature traverse at the cold end of the generator. Heat is conducted from the outer shell into the catalyst via four sets of channel fins brazed to the inside of the shell.

Table 1. Electrically Heated Generator Specifications

Shell OD	1.5 in
Shell Wall Thickness	0.049 in
Overall Length	19 in
Catalyst Length	15 in
Fin Height	7/16"
Fin Material	low-carbon steel
Catalyst Weight	7 oz
Total Generator Weight	81 oz

2.2 Electric Heater Tests

Prior to testing the electrically heated generator, an M2 burner with a prototype catalytic burner was operated on DF-2 fuel to observe its operational characteristics. The generator was preheated with an Optimus air-atomizing torch for 15-30 minutes until the core temperature of the generator reached about 600°F. The burner was able to operate with a clear blue flame without yellow tipping with catalyst core temperatures between 600-800°F. However, throughout these tests, some liquid fuel collected continually in the mixer.

After fabrication of the test generator, it was assembled between a first M2 fuel tank and a second M2 burner unit, such that its inlet was supplied with fuel from the first tank, and its vapor outlet nozzle was supplying hot vapor to the venturi of the second burner assembly.

At first, before being connected to the fuel tank, the generator was heated to 600°F at an average input of 0.62 kW. The resulting core temperature transient is shown in Figure 3.

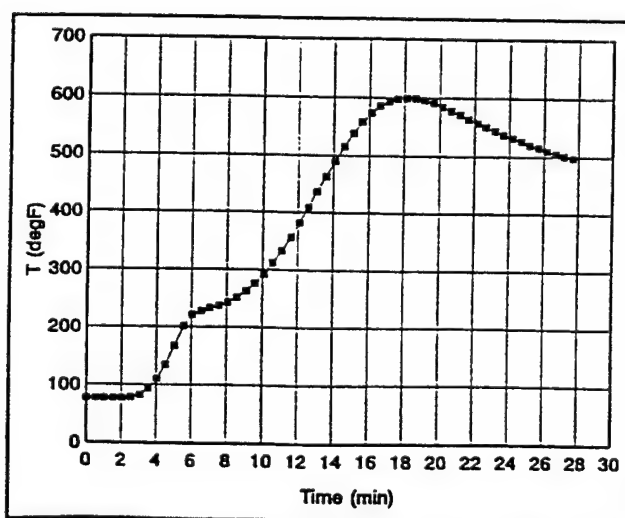


Figure 3. Core Heat-Up Transient, 0.62 kW

The plateau at around 212°F is believed to result from the desorption of water from the catalyst. The generator reached a temperature of 463°F after 13.5 minutes, requiring a total energy input of 476 Btu. This compares with a predicted energy input of 453 Btu.

A preheat test was also conducted with the fuel tank pressurized and the generator presumably full of fuel. In this case, the heater power was 1.17 kW and the catalyst reached an average temperature of 482°F in 9.3 minutes, requiring 0.182 KWH, or 622 Btu. This compares with a predicted energy input of 479 Btu. This larger discrepancy is believed to result from that assumption that the fuel only occupies the superficial void volume in the generator, weighing about 6.5 oz. That is, it assumes that the catalyst does not ab/adsorb any fuel. This is evidently a very poor assumption. If we assume that the "effective void volume" of the catalyst is 75%, then the weight of fuel in the generator would be about 11 oz, and the calculated energy is 554 Btu, which is much closer to the measured value.

The generator was allowed to reach steady-state at average core temperatures of approximately 350, 490, and 620°F, at which points the electric heat input was measured to determine the heat loss. The heat loss results are shown in Figure 4.

An axial and radial temperature traverse are shown in Figures 5 and 6. Figure 5 shows the axial temperature distribution. While there do not appear to be any clear phase demarcations, the temperature gradient appears to be steepest over the first three inches from the inlet (positions 18" - 14"), where the core fluid is heated from around 200°F up to about 350°F (which roughly corresponds to the initial boiling point of kerosine). Thereafter, the temperature rises more or less uniformly to the end of the heated length at about the one-inch point. The radial traverse rises rapidly over the first 0.4" from the fuel inlet, and then levels off at about 200°F. Considering that the initial boiling point is at least 350°F, it is evident that the entire cold end is

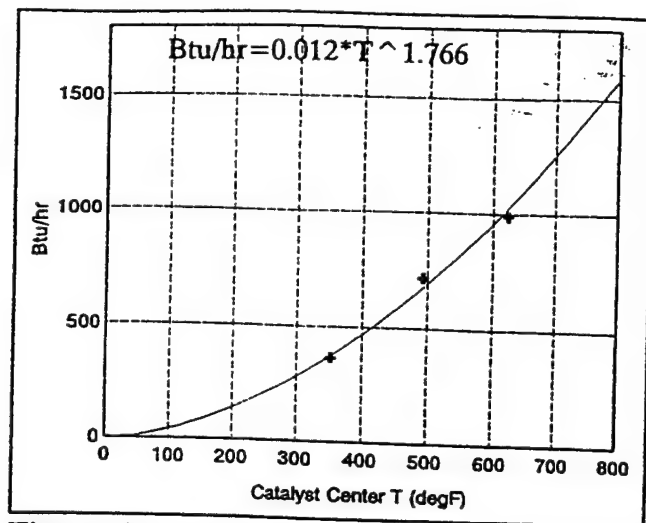


Figure 4. Steady State Heat Loss

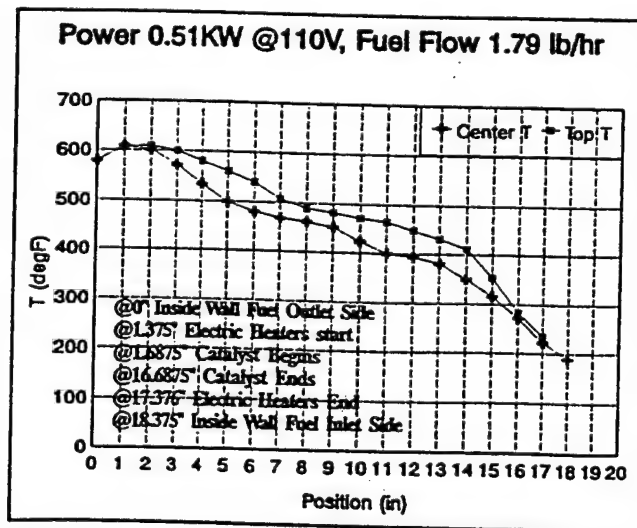


Figure 5. Converter Temperature Distribution

flooded. (This was confirmed by loosening the thermocouple fitting at the top of the tube, which resulted in liquid fuel spurting.)

The measured power input at 1.79 lb/hr fuel flow was 0.51 kW. After allowance for the 631 Btu/hr heat loss at the average jacket temperature of 474°F, the net input to the fuel was calculated to be 1075 Btu/hr, corresponding to an enthalpy rise of 601 Btu/lb.

A second test was conducted at a higher firing rate of about 4.7 lb/hr. The axial temperature profile for this test is shown in Figure 7. This is quite different from the lower input test. The gradient over the first three inches (positions 18" to 15") is quite shallow, followed by a steeper rise over the next two or three inches. The radial traverse at the fuel inlet position was similar to that at the lower input. The initial boiling point (assuming 350°F) is reached around the 12-13" position, the mid-range (assuming 450°F) is reached at the 8" point, and the end point (assuming 570°F) is not reached until the 2" point. The flow rate was not steady enough during this test to obtain an accurate measurement of enthalpy rise.

The generator tests with kerosine were rather unremarkable in that, other than an apparent preheat zone, they do not indicate any particular boiling or superheat zones having markedly different heat transfer characteristics. Rather, with the uniform rate of heat input, both the axial temperature gradient and the wall-to-catalyst temperature difference were more or less uniform. The tests indicate that the energy to heat the fuel to 600°F is about 600 Btu/lb, or roughly 120 Btu/lb more than what one would expect from a fuel with a liquid and vapor specific heats of 0.75 and 0.60 Btu/lb-°F, respectively, and a latent heat of about 90 Btu/lb. That is, the catalyst appears to add about 120 Btu/lb to the heat required to vaporize the fuel.

The electrically heated generator tests confirmed that about 600 Btu's were required to preheat the generator. A preliminary estimate showed that a metal hydride preheater system designed to deliver 600 net Btu's would weigh over 30 lb.

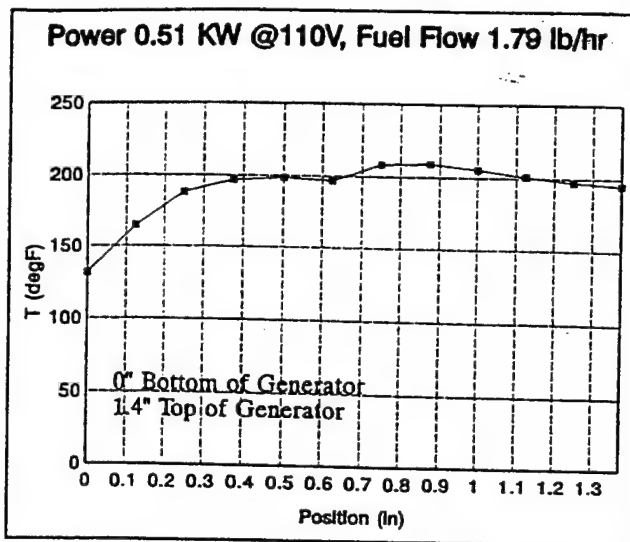


Figure 6. Radial Distribution at Cold End

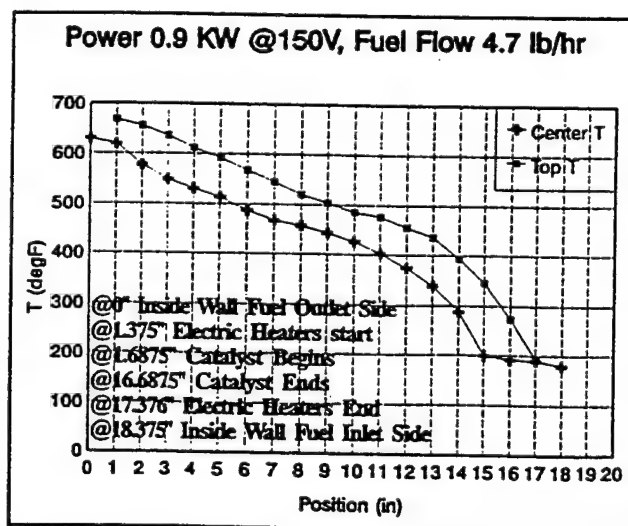


Figure 7. Axial Temperature Distribution

Furthermore, at a firing rate of 3 lb/hr, in order to regenerate the hydride within one hour, the heat input to the generator would have to be about 60% above that required for fuel vaporization (1,950 Btu/hr). These amounts were disappointingly large, and consequently, a less energy intensive approach was sought.

2.3 Revised Burner Design

Several alternative designs were considered to reduce the size and weight of the hydride system. The evolution of these designs is not described here. Suffice it to say, the concept evolved from: (1) reducing the size of burner that was required to be heated by the hydride preheater by designing a smaller hydride-heated preheat torch; (2) avoiding having to heat the entire vaporizer with the hydride preheater by preheating only the superheater and using the hot superheater as a start-up vaporizer; and (3) finally increasing the capacity of the "preheat torch" to the that of the main burner, so that only a single burner is required.

The proof-of-concept (POC) burner is illustrated in Figure 8. It comprises a central 2-3/8" OD x 3" vaporizer containing about 10 cu-in of zeolite catalyst. A 1/8" OD x 4 ft superheater coil surrounds the vaporizer, supplying vapor to a tangential 0.025" diameter fuel nozzle. A 3.83" ID x 2.5" combustion chamber surrounds the vaporizer and superheater coil. Air is supplied through a 1" diameter orifice at the base of the combustion chamber. The tangential fuel jet induces a vortex, which in turn results in a radial pressure gradient at the base of the combustion chamber. This radial pressure gradient produces a negative pressure downstream of the air orifice, which draws in the combustion air.

Prior to installation of the hydride preheater, the superheater was heated electrically by passing a current through the coil. Subsequently, the electrically heated superheater was replaced by a 1/8" OD superheater jacketed by a 5/16" OD hydride preheater.

2.4 Initial POC Burner Tests

In order to be able to specify the energy requirements of the hydride preheater, it was necessary to conduct start-up tests which simulated operation of the hydride

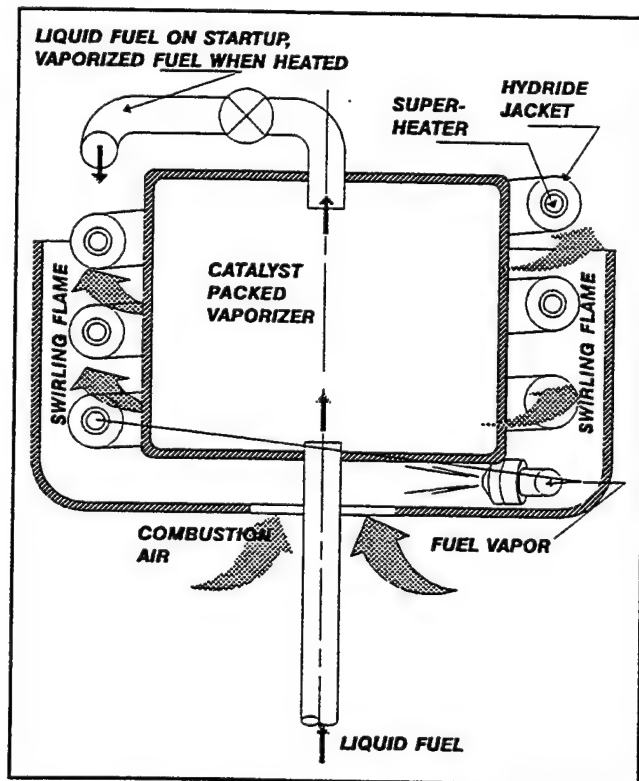


Figure 8. Proof-of-concept burner

preheater. The hydride heat input was simulated by electrically heating the superheater coil. The POC burner was configured with a 4 ft x 1/8" OD x .008" wall superheater, about 10 cu-in of zeolite in the vaporizer, a 0.025" fuel nozzle, and a 1" air orifice. The superheater was connected to a variable transformer through a 4:1 step-down transformer so that it could be heated electrically.

The initial tests were run with kerosine with a 0.025" fuel nozzle and 30 psi fuel pressure. The superheater was heated at 12 - 13 volts (240 - 280 watts) for about 10 seconds before the fuel valve was opened. The burner lit immediately. The flame surged for 5 - 10 seconds, and then stabilized. The electric heater could be turned off after about 10 seconds. The total energy used to heat the superheater amounted to only about 4 - 5 Btu.

Initially, the burner would operate stably until the vaporizer outlet temperature reached about 400 - 450°F, after which the flame would become lifty and unstable. This was determined to result from too much air. As the vapor temperature increases, the vapor mass flow rate decreases, but the vapor velocity increases, entraining proportionally more air. Thus the flame gets leaner.

A rudimentary air shutter was installed to reduce the air flow. This cured the lifty flame. The firing rate was estimated to be about 30,000 Btu/hr. The flame was blue with no yellow tips. The visible flame extended about 1" - 2" above the combustion chamber, about level with the top of the vaporizer. With the air shutter in place, the vaporizer temperature increased steadily to about 500°F after about 5 minutes. At this point, the bottom half of the superheater and the fuel nozzle were cherry red, and the burner was shut down.

A shut-off valve was used to close off the inlet to the superheater. At shut-down, a small amount of fuel remained in the superheater, and the flame extinguished with a small yellow sooty flame for about 2 - 3 seconds.

The high superheater temperature was a concern. To reduce the amount of superheat, the length of the superheater was reduced to 23". This did reduce the superheater temperature. However, the shorter superheater was now prone to flooding at startup.

This configuration was next tested with DF-2, with fuel orifices ranging from 0.028" to 0.031". The burner lit with a yellow flame. After several minutes, the flame length shortened and became blue. The superheater was even more prone to flooding than with kerosine.

The 4 ft superheater was replaced, and the nozzle size was changed to 0.0295". The superheater was electrically preheated for 20 seconds at 222 watts, consuming approximately 6.3 Btu. The burner lit cleanly with a yellow flame, which soon changed to blue. The vaporizer temperature rose continually, levelling off at about 740°F after 20 minutes. The firing rate was 31,000 Btu/hr. A trace of vaporizer outlet temperature versus time is shown in Figure 9.

The firing rate of the present configuration is limited by the air flow admitted through the 1" air orifice. While it is possible that the capacity might be further increased by enlarging the air orifice, it is felt that the present 31,000 Btu/hr output is close to the limit for the 3.8" ID combustion chamber. For 60,000 Btu/hr, the ID should be about 6". It was therefore decided to test the proof-of-concept hydride preheater with this burner, and to size it for about 30,000 Btu/hr.

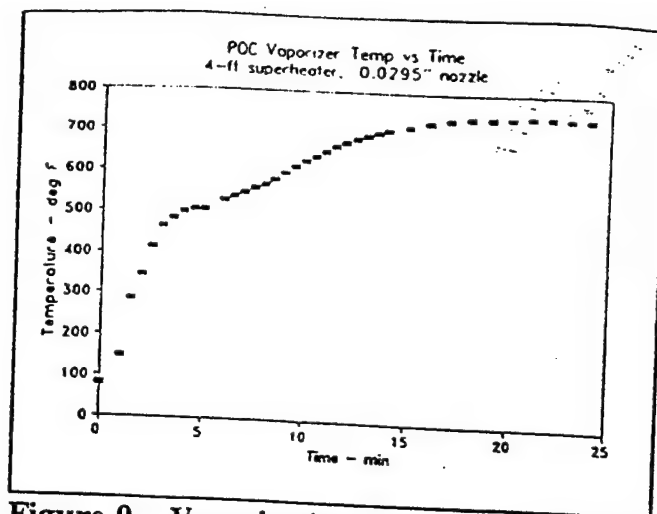


Figure 9. Vaporization Temperature versus Time

2.5 Hydride Preheater

Based upon the test results with the electrically heated superheater, the hydride preheater design requirements listed in Table 2 were developed. The jacketed length of 34" was based upon the electrically heated superheater tests, which indicated that this length should be about the minimum necessary to prevent flooding at start-up. The 20-30 Btu of energy net of the amount required to raise the superheater to 400°C was considered to be necessary to provide for some vaporization of fuel before the burner flame could provide the necessary heat.

The metal hydride preheater coil was designed and fabricated by the subcontractor, Ergenics, Inc. The POC preheater was constructed of 316 stainless steel tubing¹. It consists of a 1/8" OD superheater tube jacketed by a 5/16" OD hydride jacket, coiled to approximately 3-1/8" pitch diameter. It contains 5.5 grams of hydrogen stored at a pressure of about 50 psia. The total assembly weight including source bed and valving is 4.7 kg. The preheater coil contains 77 grams of hydride alloy, and the source bed contains 1743 grams. Fully charged, the source bed can hold 17 grams of hydrogen at a pressure of 176 psia.

The design specification called for a reserve capacity of 20-30 Btu. The preliminary test results by Ergenics indicated that there was little if any reserve heating capacity in the coil after it has reached temperature. Thus, any energy for vaporization of fuel must result in cooling of the walls of the superheater and the hydride jacket, possibly supplemented by additional hydrogen adsorption as the hydride alloy cools. Ergenics' analysis of the thermal performance of the prototype hydride preheater is given in Appendix.

¹ A more heat resistant alloy might be desirable. However, this was not feasible for the prototype given the small quantity and lead-time.

Table 2. Hydride Preheater Design Requirements

Coil Pitch Diameter	3-1/8"
Number of jacketed coils	3.5
Number of unjacketed coils	2 at inlet to preheater
Jacket OD	5/16"
Jacket wall	0.015" - 0.020"
Inner tube OD	1/8"
Inner tube wall	0.008" - 0.010"
Preheat Temperature	400°C
Net Heat Output	20 - 30 Btu
Heat Output Rate	0.3 Btu/sec
Maximum wall temperature	approx. 900°C
Minimum wall temperature	approx. 500°C

2.6 POC Burner Tests

The POC preheater/superheater consisted of one turn of 1/8" OD tubing feeding the 5/16" OD x 34" long hydride-jacketed preheater section containing of 3.5 turns, followed by about 1/2 turn of 1/8" OD tubing terminated by a 0.029" ID fuel nozzle. As supplied, the ends of the jacketed section would not fit within the 3.6" ID of the original POC combustion chamber. Consequently, the combustion chamber was replaced with a 4-1/8" OD x 3-5/8" high x .030" thick stainless steel cup.

The preheater/superheater assembly consisting of the 3.5 coils of preheater and 1.5 coils of superheater tubing was installed in the modified burner. The burner assembly was instrumented with a 1/8" OD type K thermocouple immersed in the catalyst-packed vaporizer, and a 0.020" OD sheathed type K thermocouple wired to the outside of the preheater jacket. Temperatures were sampled at one second increments via a data logger.

A typical temperature history is shown in Figure 10. The valve between the source bed and the preheater was opened, and the preheater would rapidly heat, reaching a temperature of about 700°F in about 15 seconds. The fuel valve was then opened, and the burner was ignited with a torch. Ignition was clean, producing a bushy yellow flame that extended about 6" upward and 4" radially from the burner. This bushy yellow flame would persist for about 5 minutes or more, depending upon the firing rate, until the vaporizer temperature reached about 500°F. Thereafter, the flame size would shrink until it was more or less contained

within the combustion chamber cup, and the flame would become blue. The vaporizer would gradually rise to a temperature of over 700°F. As the temperatures rose, the flame color shifted from yellow to blue, indicating continually increasing excess air.

Immediately upon ignition, the thermocouple recording the preheater temperature would first rise about 100°F, would then drop a smaller amount, and then would gradually rise to a final steady state temperature approaching 1600-1800°F. Since this thermocouple was only

poorly thermally bonded to the jacket, its temperature was influenced significantly by the flame, and should not be interpreted as indicating the actual jacket temperature. Based upon the red color of the preheater jacket, its temperature was estimated to be about 1500°F. Generally, the burner would be operated for from 20 to 40 minutes to assure regeneration of the hydride source bed.

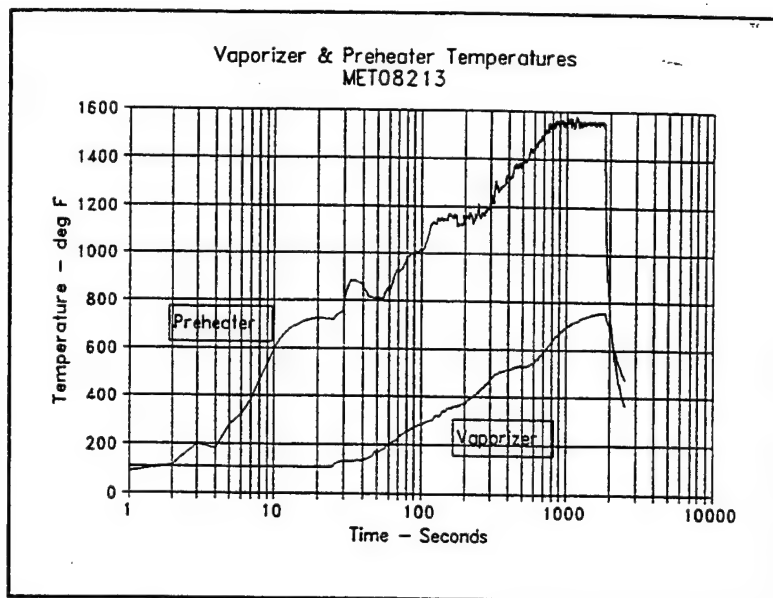


Figure 10. Preheater and Vaporizer Temperatures

Subsequently, a series of tests were conducted to determine the minimum firing time necessary to regenerate the preheater and source bed. The superheater/preheater temperatures of the tests are shown in Figure 11, curves 1-5. The superheater was heated to around 700°F in about 10-15 minutes. Next, fuel would be admitted to the preheated superheater, and the burner would be ignited and allowed to operate for 15 minutes (curve 1) down to 2 minutes (curve 5) to regenerate the hydride source bed.

In the initial 15-minute test, the fuel nozzle was partially plugged, resulting in a low, erratic firing rate. Nonetheless, the superheater/preheater was eventually heated to about 1,200°F by the burner. In the subsequent test (curve 2), the preheater only reached about 650°F at start-up, but the burner ignited successfully. Next the burner was allowed to operate for 5, 4, 3 and 2 minutes (curves, 2, 3, 4, and 5, respectively). In the next 2 tests, the preheater reached over 700°F at start-up, and was heated to 1,200-1,600°F by the burner before shut-down. In the last test, curve 5, the preheater reached only about 650°F at start-up, and only about 1,100 when the burner was shut-down. On the subsequent attempt at ignition, the burner flooded when ignition was attempted, indicating insufficient energy for vaporization.

These tests showed that the preheater can be regenerated in as few as 3 minutes, and still relight cleanly on the subsequent try. At two minutes regeneration time, the vaporizer will flood.

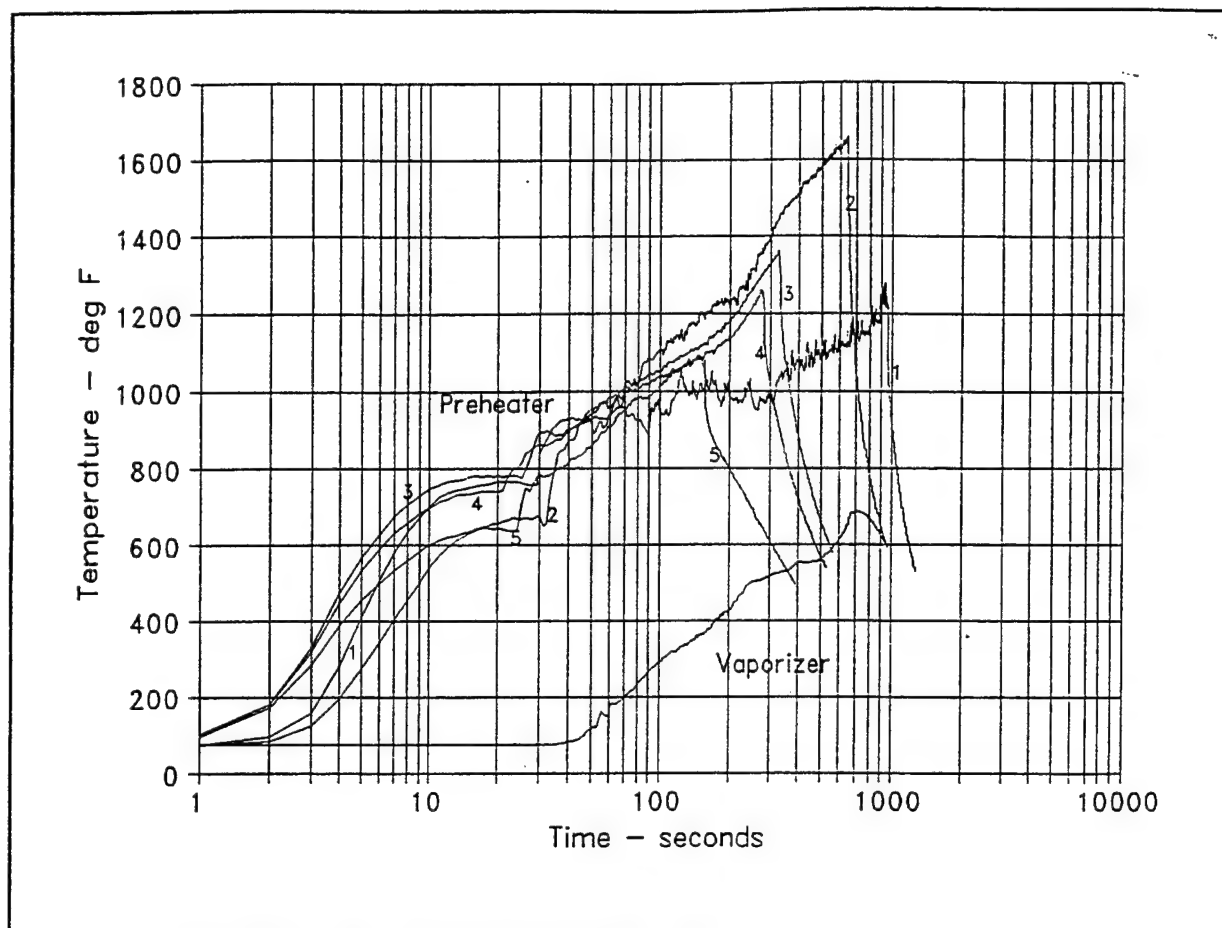


Figure 11. Preheater and vaporizer temperatures

The tests also indicated that the hydride preheater must be heated to a temperature of at least 1,200°F in order to regenerate the source bed. A slight increase in the slope of the preheater temperature versus time can be seen in Figure 11, occurring in the vicinity of about 1,200°F. This could be indicative of the end of regeneration of the preheater.

3. EVALUATION OF HYDRIDE PREHEATER BURNER

3.1 Discussion of Test Results

The final test results demonstrated that the low-mass metal hydride preheater/superheater can provide rapid start-up and clean combustion. The time required to preheat the burner with the metal hydride is on the order of only about 10-20 seconds, compared to the several minutes required to heat the generator of the M2 cookstove with the present preheat torch.

Once the burner is lit, there is a period on the order of about 10 minutes while the catalytic generator is being heated by the burner, during which time the flame burns with a large yellow flame. As the vaporizer heats, the flame shrinks in size and becomes blue. Although the flame was yellow, it did not appear to be smoky. It is quite possible that the flame color could be better controlled with higher oxygenation during warm-up, together with an air shutter to reduce air flow at steady-state.

The superheater coil acts as a vaporizer during start-up and while the main catalytic vaporizer is being heated by the burner flame. As the vaporizer is heated, the temperature of the fuel entering the superheater increases. By the time the vaporizer reaches about 700°F, the superheater temperature may exceed 1,600°F. The temperature-time curves of Figure 11 appear to maintain a more or less constant temperature difference between the preheater/superheater and the vaporizer of about 800°F.

The burner flame appeared steady at all times, with no evidence of surging, as is sometimes seen in coil-type vaporizers.

The preheater appeared to be very resistant to flooding, provided there was sufficient preheat. This characteristic appeared to be more pronounced in the hydride-jacketed version than in the bare electrically-heated coil. This is most likely due to the greater thermal mass of the hydride jacket. It is also possible that vaporization of the fuel may be assisted at start-up by continued adsorption of hydrogen in the jacket as the jacket is cooled by the fuel.

There were several instances of carbon particles blocking the fuel vapor nozzle. These carbon particles were undoubtedly formed in the superheater, since the inlet to the superheater was protected by a filter-strainer. Since the nozzle had no provisions for cleaning a blockage, it was necessary to shut-down and disassemble the nozzle in each instance. As it is unlikely that the formation of carbon particles can be prevented in the superheater, a large-capacity filter-strainer will be required upstream of the vapor nozzle to prevent fouling.

The POC burner was equipped with a fuel shut-off valve located between the vaporizer and the superheater. When this valve was closed to shut-off the burner, the flame would be extinguished with almost no delay. However, a small wisp of black smoke would remain for a few seconds. If this wisp of smoke is considered objectionable, it will be necessary to move the valve to a position immediately ahead of the fuel nozzle, as in the present M2 burner.

At steady-state, the flame is contained within the 4-1/8" diameter bowl in the POC burner. The bowl reached a dull red temperature, estimated to be in the range of 1,300-1,500°F. Stainless steel should be sufficiently serviceable for this application.

Regeneration of the preheater was accomplished within about 3 minutes, which is less time than it took to fully heat the vaporizer. Therefore, unless the burner operation is aborted for

some reason, regeneration of the preheater should be a routine matter. In the event of an aborted light-off, a back-up means of starting the burner will be required.

The POC burner does not require a venturi mixer to entrain primary combustion air. Instead, it creates a vortex flame that generates a low pressure at its axis. By locating the air inlet port at the burner axis, the combustion air is drawn into the burner by the low pressure. As the vortex has a relatively high velocity, the burner is noisier than the M2 - similar to a blow torch. The noise is probably inherent to the swirl burner concept - it is not inherent to the hydride preheater/superheater approach.

3.2 Preferred Design Approach

Based upon the design, development, and test results of this Phase I study, the following conclusions have been reached concerning the preferred approach to a metal-hydride preheated burner.

The initial concept of heating the catalytic generator (vaporizer) with the metal-hydride preheater proved to be too energy intensive. The net energy requirement² would have been about 600 Btu, requiring a preheater and source bed weight of over 30 lb.

The size and weight of the hydride preheater is minimized by preheating only the superheater coil of the burner, which weighs under 20 grams in the POC burner. Allowing for a larger capacity superheater in a 3 lb/hr burner, the superheater weight should not exceed about 40 grams (0.1 lb).

A temperature of at least 1,200°F appears to be necessary to regenerate the preheater. In order to reach this temperature within a reasonable length of time, the steady-state vapor temperature must be hotter than 1,200°F.

The POC burner retained the catalytic vaporizer. It is noted, however, that this vaporizer is not required for start-up, and it has a considerably longer time-constant than the preheater/superheater. Since it appears necessary to heat the vapor to a temperature in excess of about 1,200°F in order to regenerate the preheater, one may question the need for the catalytic vaporizer.

Although the need for the catalytic vaporizer may be questioned, some sort of vaporizer separate from the hydride-jacketed preheater/superheater is likely to be required. Since the preheater must be heated over 1,200°F for regeneration to occur, unless the fuel entering the preheater is vaporized at steady-state, it is unlikely that the inlet of the preheater will get hot enough to regenerate.

² Net energy above that required to heat the preheater, i.e., available to heat the generator.

If the catalytic generator is eliminated, the ideal replacement would be an unjacketed length of tubing designed to heat the fuel to a temperature sufficient to raise the jacket temperature to 1,200°F at the inlet of the preheater. This would have a very short time constant and should greatly reduce the length of time required to reach steady-state.

3.3 Preliminary Design

A preliminary design of a 3 lb/hr metal-hydride preheated cookstove burner is illustrated in Figure 12. The design is similar to but slightly larger than the POC burner, which had a capacity of about 1.5 lb/hr. This design shows a coil-type vaporizer, which is similar to the superheater, but is unjacketed. This should be expected to reach steady-state blue-flame operation much sooner than a more massive catalyst-packed vaporizer. As in the POC burner, the fuel vapor is injected into the combustion chamber bowl tangentially, thereby inducing a vortex flame. The low pressure at the center of the vortex induces the combustion air. The combustion air can be controlled by a shutter (not shown). A filter/strainer protects the fuel valve and nozzle from carbon debris than may be formed in the vaporizer and superheater.

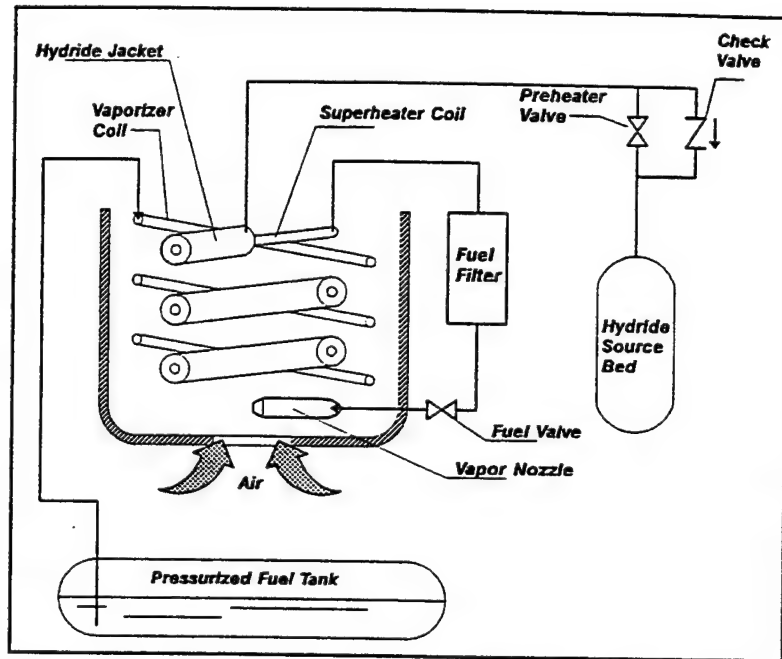


Figure 12. Preliminary design of 3 lb/hr burner.

The 3 lb/hr burner bowl is expected to be about 6" diameter x 4" high. The vaporizer and superheater coils are estimated to be about 1/8" - 3/16" diameter and about 3 ft long. Thus, with a 4" - 5" pitch diameter, the coils would consist of 2-1/2 to 3 turns. The hydride jacket is expected to be 5/16" - 3/8" OD, with a capacity of about 7 - 10 grams of hydrogen. The weight of the hydride sub-system should be about the same as that of POC preheater - that is, about 10 lb. Since the swirl burner is but a fraction of the weight of the cast-iron M2 burner, the overall system weight including the hydride system will be significantly less than that of the M2 burner.

Operation of the burner would be similar to the POC burner. The jacketed superheater would be preheated by opening the hydride valve. After about 10-15 seconds, hydride valve could be released, allowing it to close automatically. The fuel valve would be opened,

admitting liquid fuel through the vaporizer coil to the superheater. The fuel would be vaporized in the hot superheater, and the fuel vapor issuing from the vapor nozzle would be ignited with a match or other igniter. The burner flame would immediately heat the vaporizer and jacketed superheater. As the hydride jacket is heated, the hydride source bed would be regenerated as the hydrogen is desorbed from the jacket and flows back to the source bed via the check valve.

In the event of an aborted start in which the source bed is discharged, some means must be provided for regenerating the bed. Several options are available, which should be evaluated in Phase II. These include:

- An auxiliary torch, similar to the air-atomizing Optimus burner, that would preheat the vaporizer and superheater sufficiently to permit ignition of the burner.
- A burner cup in the base of the combustion chamber bowl that would hold a small amount of fuel sufficient to preheat the vaporizer/superheater. While it would burn with a large, smoky flame, this would be tolerable under the rare circumstance that the hydride preheater is unavailable.
- A pair of electric contacts that would permit the vaporizer and/or superheater to be "jump started" with a battery.
- A spare hydride preheater and fuel train. This could be used to light the burner, and the discharged preheater could be regenerated in the burner flame.

4.0 CONCLUSIONS

The main conclusion of the Phase I study is that the hydride preheater should be a practical means of obtaining clean and rapid ignition of a diesel cookstove. Additional significant conclusions are:

1. In order to minimize the size and weight of hydride system, the thermal mass of the vaporizer utilized at start-up should be as small as possible. A superheater coil that serves to vaporize the fuel at start-up appears to satisfy this requirement.
2. Since the hydride preheater must be raised to a high temperature for regeneration, and since heating the fuel to a similar temperature appears to be unavoidable, the need for a catalytic vaporizer that gasifies a portion of the fuel is less apparent.
3. A compact and lightweight swirl-type burner has been demonstrated that achieves clean and rapid start-ups and stable operation.

4. The combination of the metal hydride preheater system and the swirl-type burner should provide a lighter-weight, more compact, and cleaner starting burner for diesel fuel than the present M2 gasoline burner.
5. The new burner should be lighter, more compact, and considerably less expensive than forced-draft atomizing oil burners, and will be capable of operating without electricity. Start-up should be as clean as an atomizing oil burner, and should require only a few seconds longer to ignite.
6. It is recommended that a prototype 3 lb/hr burner and the necessary auxiliary components and controls be developed and demonstrated in Phase II.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-*991021* in a series of reports approved for publication.

APPENDIX

Ergenics Phase I Report

Prototype Hydride Diesel Fuel Preheated
Phase I - Final Report
October 23, 1997

Introduction

As a subcontractor to AMTI on a first phase SBIR, U.S. DOD contract #DAAK60-97-C-9203, Ergenics designed and fabricated a metal hydride cold start diesel fuel preheater for use in Army field stoves. This report describes the design of this novel preheater and suggests some areas of improvement that may optimize the unit's performance. The hydride heater was successfully tested by AMTI, the results of which are reported elsewhere.

Hydride Preheater Operation

Metal hydride preheater technology is based on the exothermic reaction that occurs when hydrogen gas comes in contact with certain metals. The hydrogen is absorbed by the metal creating a new metal alloy, a metal hydride. When this happens, the heat of reaction can be substantial, quickly raising the temperature of the metal hydride alloy and it's container. The temperatures reached by this reaction are determined by the metal hydrides used, and thus are controlled and repeatable. This reaction is reversible, with hydrogen being released when heat is applied to the hydride alloy. References 1 and 2 will give the reader a more detailed description of metal hydride technology.

The operational schematic for the hydride preheater is shown in Figure 1, and essentially consists of four key components as follows :

- 1) The hydride "source" bed.
- 2) The hydride heater coil.
- 3) A shut off valve located between the two hydride beds.
- 4) A one way "check" valve located between the two hydride bed

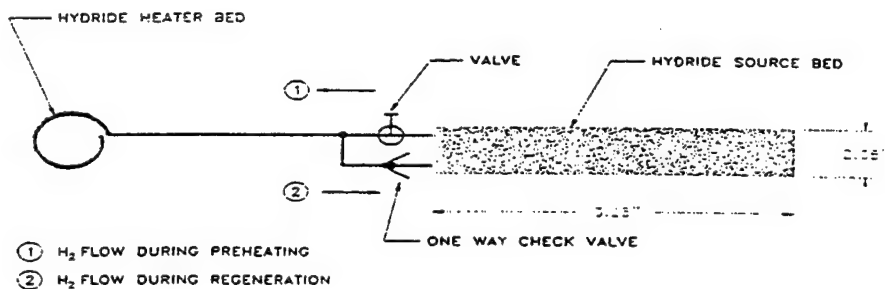


FIGURE 1-A : OPERATIONAL SCHEMATIC OF HYDRIDE PREHEATER

The hydride source bed stores a small amount of hydrogen in a ambient temperature metal hydride alloy. When diesel fuel preheating is desired, the manual valve is opened allowing the hydrogen to flow from the source bed to the hydride heater bed, which is located in the diesel fuel combustion nozzle. The hydrogen is quickly absorbed by the heater hydride resulting in a rapid rise in the temperature of the hydride alloy, which in turn heats up, and vaporizes, the diesel fuel (about 350°C). After successful diesel fuel burning is accomplished, the manual shut off valve is closed. In a few minutes the temperature of the burning diesel fuel is hot enough to raise the temperature of the hydride heater alloy above it's preheater temperature, enabling hydrogen flow from the heater alloy through the one way check valve back to the hydride source bed. The one way check valve will permit hydrogen flow when ever a pressure differential of 1 psig exists in its flow direction, but will not permit hydrogen flow in the reverse flow direction, this allows the preheater to be passively regenerated, without the need for active and complicated electronic control. Figure 2 is a photograph of the fabricated prototype.

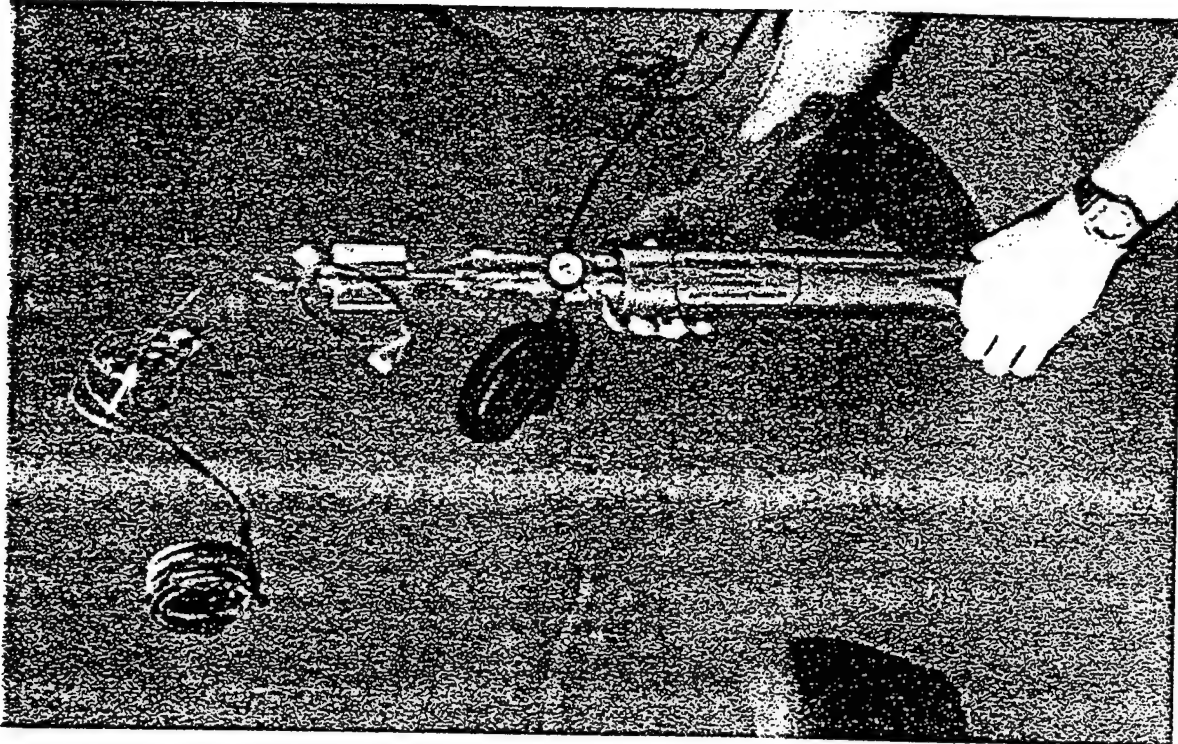


FIGURE 2-A : PROTOTYPE HYDRIDE PREHEATER

Hydride Preheater Component Description

Hydride Source Bed :

A photograph of the hydride source bed is shown in Figure 3. This container consists of a 2.35" diameter, 13.25" long 304 SS tube that contains 1,818.7 grams of hydride alloy #T-83584-2. The total mass of the completed hydride source bed is 3,766.6 grams. The source storage unit is greatly over sized (by a factor of 10) to provide the sensible heat needed to minimize the temperature drop of the storage unit during preheater activation. A PCT curve for this storage unit is shown in Figure 4 and shows that about 15 grams of hydrogen can be stored in a fully charged unit. The actual amount of hydrogen transferred during preheating is about 1 gram. Future hydride source beds will use higher heat capacity, non hydride materials to minimize bed size and mass. It is expected that an optimized source unit, that transfers 1 gram of hydrogen during preheating, will have a mass of only 500 grams and a volume of 200 cc.



FIGURE 3-A : HYDRIDE "SOURCE" BED

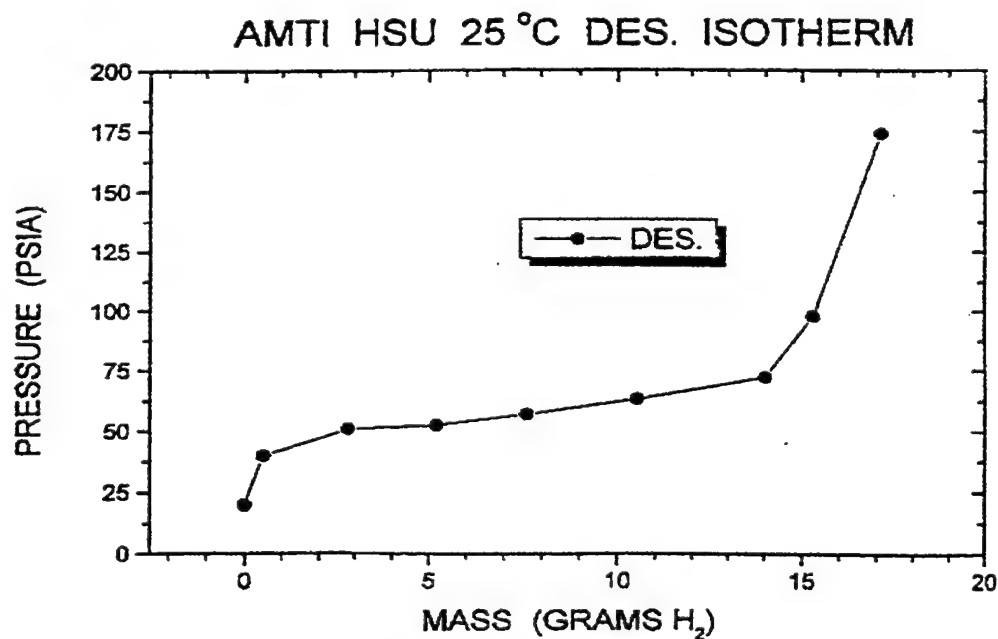


FIGURE 4-A : PRESSURE / CAPACITY CURVE THE HYDRIDE SOURCE CONTAINER

Hydride Heater Bed :

The hydride "Hot" heater consists of a 5/16" OD, 34" long stainless steel tube as the outer containment tube for the metal hydride alloy. Originally this tube wall thickness was designed to be 0.015", but was increased to 0.016" when it was determined that 0.015" wall tubing was not readily available. Concentricly housed inside this 5/16" tube is the metal hydride alloy, the 1/8" (0.010" wall) diesel fuel tubing and a hydrogen distribution/filtration mechanism. All four of these components are related to each other, with minor changes in one component effecting the effectiveness and even the operation of the prototype. The prototype was designed to provide at least 20 Btus of net external energy; energy that would be available for additional diesel fuel heating, after the unit has reach it's actuation temperature of 400°C. Figure 5 is a close up photograph of the heater bed.

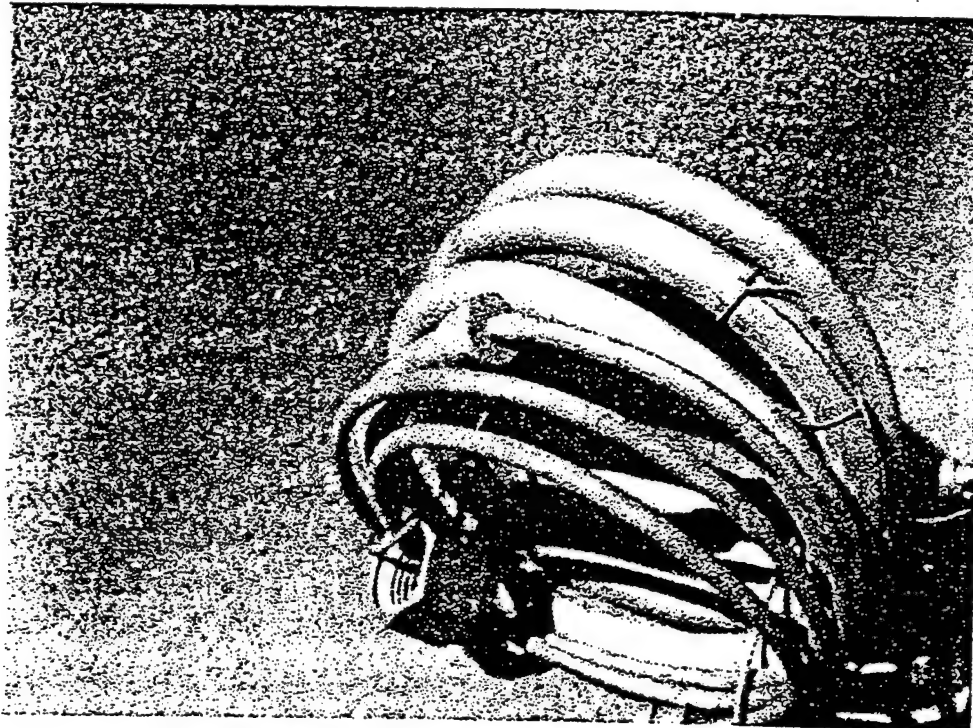


FIGURE 5-A : HYDRIDE HEATER COIL

Actuation Valve and Regeneration Check Valve :

Figure 6 is a close up photograph of the actuation valve and check valve for the preheater. These valves are attached to one end of the hydride source unit.

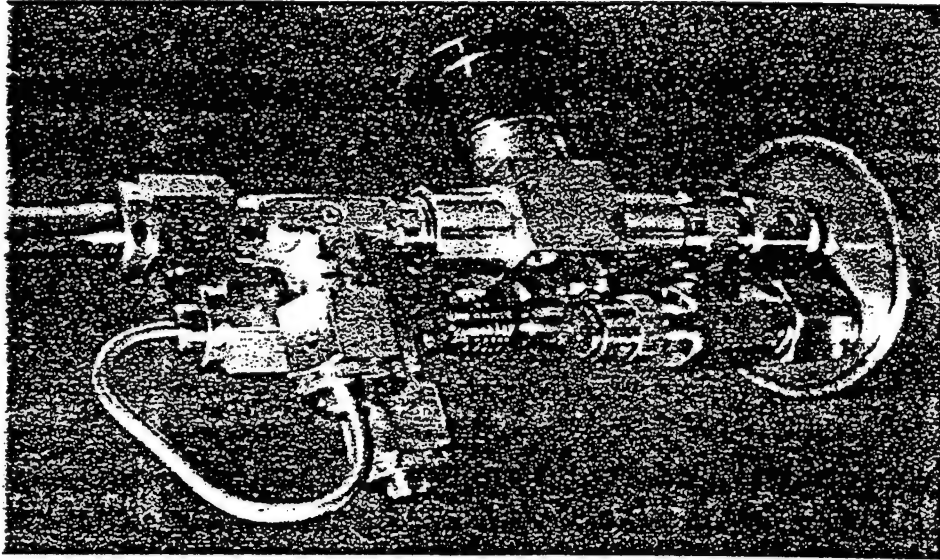


FIGURE 6-A : ACTIVATION AND ONE WAY CHECK VALVES

Preliminary Temperature Test

Figure 7 shows the plot of temperature vs time for a thermocouple placed at the midpoint of the hydride tube. Figure 8 is a detailed look at the first 100 seconds of this plot, and shows that internal heating of the tube appears to stop after about 20 seconds into the operation of the unit. This 20 seconds corresponds to about 8.3 Btus (assuming a convective heat transfer coefficient of $10 \text{ Btu}/(\text{Hr } ^\circ\text{F Ft}^2)$) of external net energy from the hydride tube, less than the expected 20 Btus.

**AMTI HOT COIL TEMP. CURVE
FROM HYDROGEN STORAGE UNIT**

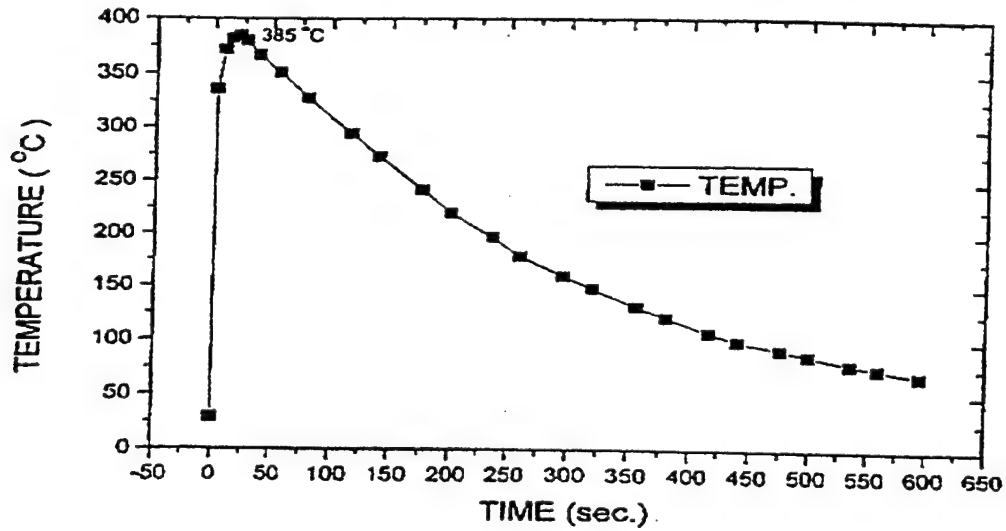


FIGURE 7-A : TEMPERATURE CURVE DURING PREHEATER OPERATION

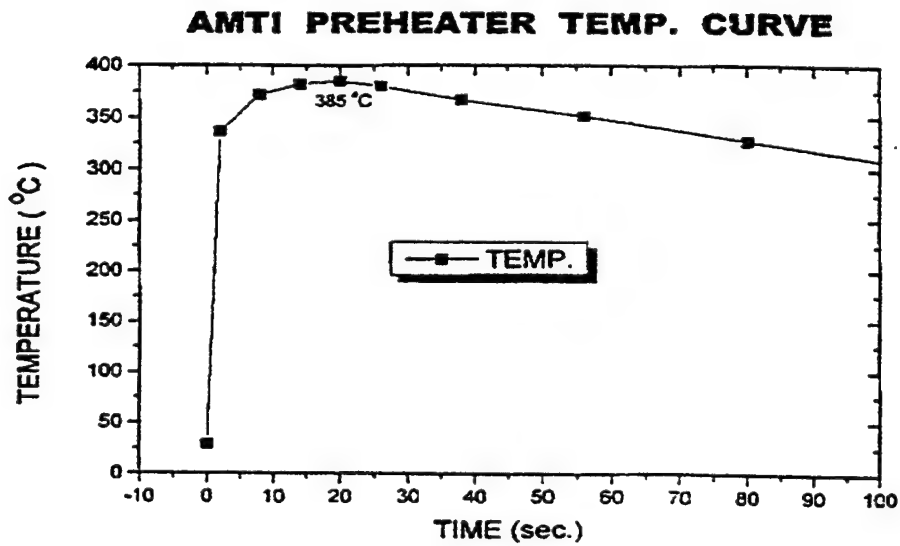


FIGURE 8-A : TEMPERATURE CURVE DURING THE FIRST 100 SEC. OF OPERATION

Prototype Fabrication Refinements

Mass of Hydride Alloy in Unit:

The completed prototype contains only 77 grams of heat producing hydride alloy which is 18 grams less than the 95 grams expected and on which the design was based. Reasons for this alloy fill deficiency are not yet known, except to say that the specific design of this hydride unit had never been built before. Reasons for continuing with the fabrication of the prototype after this deficiency was observed were :

- 1) It was feared that the process of removing the metal hydride from the unit might damage the intricate and light weight hydrogen distribution and filtration mechanism used in this prototype.
- 2) The hydride fill procedure used was deemed to be adequate for this design. Also, it was believed that a better fill procedure could not be determined and tested in the desired time frame.

The estimated loss of net heat due to this loss of hydride is 7.02 Btus.

Hydrogen Capacity of the Hydride Alloy :

Due to the desire to use economical materials in the eventual commercial diesel fuel preheated, more economical metals were used in the melting of the metal hydride alloy. This resulted in a alloy with about 15% less hydrogen storage capacity than expected. This loss of hydrogen capacity may have resulted in a loss of 7.4 Btus of net heat energy.

5/16" Diameter Hydride Tube :

As described earlier, due to the inability to find a 0.015" thick walled 5/16" hydride tube, a slightly thicker (0.016") tube was used. This resulted in slightly less hydride being stored (about 2 grams), and slightly more parasitic metal to heat up. The net result is about 1.5 Btu net heating loss.

Summary of Heat losses :

Adding these heat losses,

"Observed" net heat from prototype	=	8.3 Btu
15% less Hydrogen capacity in alloy	=	7.4 Btus
23% less hydride fill in prototype	=	7.02 Btus
Slightly thicker 5/16" tube used	=	1.5 Btus
Total		<hr/> 24.22 Btus

Of this 24.22 Btus, only 8.3 Btus of net energy heating was observed after the prototype got up to operating temperature. Therefore, the hydride preheater is about 11.7 Btu short in producing the desired 20 net Btus, and about 15.92 Btus short in producing the designed 24.22 net Btus..

Future Design Changes to Compensate for the Losses seen in the 1st Prototype

Redesigning the hydride preheater to increase it's net heating output can be pursued several ways, either individually or together. Before these paths are listed we should point out a couple of design criteria that were apparently successful. They are...

1) Bending of the hydride coil :

In the fabrication of very light weight hydride devices there is a concern in bending the final product without damaging the unit, such as buckling the 5/16" outer tube, or damaging the inner hydrogen distribution/filtration mechanism. The prototype appears to have been successful in both of these concerns which suggests that further weight reduction in "parasitic" containment hardware might be possible (I.e: perhaps a thinner walled 5/16" tube is possible)

2) Adequate Hydrogen Gas Distribution to the Hydride :

Adequate hydrogen flow to the metal hydride alloy is critical For quick and effective preheater operation. As can be seen in Figure 1, the quick rise in temperature of the hydride tube upon valve actuation suggests that the hydrogen distribution/filtration mechanism used in this 1st prototype appears to have been successful, however, further testing of the unit should be conducted before this conclusion is made. Of great importance is the temperature

profile of the hydride tube at the very end of the hydride tube, the point furthest away from the hydrogen inlet. If the temperature response time is adequate here, then this may suggest that a refinement of the hydrogen distribution system may be possible in order to allow for more hydride in the tube.

Listed below are some possible improvements that could be made in the design and fabrication of future hydride diesel fuel pre-heaters.

- 1) As mentioned earlier, the prototype contained only 77 grams of the desired 95 grams of hydride alloy. It is believed that the internal geometry of the hydride tube impeded optimum hydride mass containment. Tests should be conducted to see if different hydride insertion techniques would be more successful in increasing hydride storage density. Estimated net heat generation due to this change would be 7.02 Btus more than the heat generated by the 77 grams in the 1st prototype.
- 2) It is known that greater hydride storage densities can be achieved by using a finer and/or mixed mesh of hydride material. However, it is believed that the hydrogen distribution/filtration mechanism should be redesigned, so that successful containment of the hydride is maintained. Estimated net heat generation due to this change would be 12.6 Btus more than the heat generated by the 77 grams in the prototype. This change alone may yield the net 20 Btus desired for the unit.
- 3) A lighter massed unit may be possible using thinner walled tubing. This would lessen the parasitic heat losses and provide more volume for hydride material. However, this change would open the door to questions of successful tube bending.
- 4) Improvements in hydrogen/alloy capacity may be possible.

Minimum Size Estimates for 0, 10 and 20 Btu of Reserve Energy

Rough estimates of how the outer geometry of the hydride heater coil might change for different amounts of reserve energy (energy remaining after the hydride preheater coil has achieved preheat temperature) were calculated. These estimates assume that none of the above improvements are implemented, but that the heater is simply sized according to the performance of the first prototype, and that the length of the prototype remains unchanged at 34 inches. The current prototype has a diameter of 0.3125 inches and provides about 8.3 Btus of reserve energy.

Reserve Energy of Heater Coil (after preheating to 385°C)	Estimated Diameter of Heater
0.0 Btu	0.2765 inches
8.3 Btu	0.3125 inches
10.0 Btu	0.3220 inches
20.0 Btu	0.3605 inches

Above is a plot of the estimated outer diameter of the heater hydride tube vs the reserve energy capacity of the preheater. As stated previously, these estimates are considered to be conservative since improvements due to better alloy packing and a more optimized container design were not considered. In addition, heater tests using shorter lengths of hydride preheater coils should be conducted to see if heater performance can be improved and optimized.

Preheater Cost Estimates in Mass Production

The following are ballpark cost estimates for the hydride preheater when produced in mass. Please note that these estimates assume the use of the more economical hydride alloys that were developed for this program, and were used in the prototype.

Units per Year	Estimated Cost per Unit
10,000	\$ 105.00
50,000	\$ 82.00
100,000	\$ 77.00